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No. 865.

IMPACT TESTS OF STRUCTURAL STEEL.

By S. Bent Russell, M. Am. Soc. C. E.

Presented October 4th, 1899.

WITH DISCUSSION.

In this paper will be given the results of some impact tests of small specimens of wrought iron and soft steel. The tests were made by a new method, under which the specimens were broken by tensile stress.

The matter to be presented will be given in its natural order, beginning with a few words on the need of tests of this character. The theory of the methods will then be given, followed by a description of the appliances used in the tests. The results of the experiments will then be stated, and, lastly, the conclusions that may be drawn from the observations.

Now, as to the need of study on the effect of impact on steel, if we leave out the engineers, the average man would be found to think that the strength of steel was its most important quality. Engineers, however, do not take the same view of the matter. To give an illustration, a well-known and experienced engineer once remarked to the author, that in ordinary engineering work he cared but little about the tensile strength of the steel he was to use, as compared with the general

reliability of the metal, *i. e.*, its uniform toughness and ability to withstand shocks and distortion.

This view is, without doubt, held by the majority of experienced engineers. In fact, it may be said, that among engineers the importance of shock resistance is generally admitted. Most engineers, however, will be found content with the methods now in use for determining the shock resistance of steel. They will contend that any skilful blacksmith can test a sample of steel and say whether or not it is tough and reliable.

There is, on the other hand, among engineers and scientific men, a rapidly growing feeling as to the importance of impact tests of structural materials, made, not with the blacksmith's methods and muscular sense, but in accordance with the stricter rules of experimental science. No argument is needed, then, to show that at this time studies of the effect of impact on steel are quite in order, and that the first step is to seek a satisfactory method of testing steel. The hope of finding a method which would be in advance of present practice has led to the experiments herein given.

Theory of the Methods Used.

The following description, with Figs. 1 to 5, shows how the new design may be evolved, step by step, from the old type of impact machine.

Fig. 1 shows in outline the familiar form of impact testing machine, where the test bar rests on two rigid supports and is struck in the middle by a falling weight. Owing to the rigidity of the knife-edges, *K*, the energy of the blow must be absorbed in deflecting the test piece *F*.

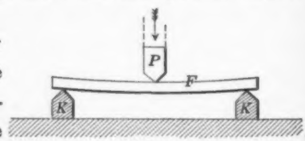

Fig. 1.

Suppose, now, a set of conditions where the bar *F* is comparatively rigid, and, in place of one of the knife-edges, there is a yielding support or spring *S*, as shown in Fig. 2. The energy of the blow from the falling weight *P* will now be absorbed in compressing the spring *S*. This will be strictly true only where the bar *F* and the remaining knife-edge *K* are perfectly rigid.

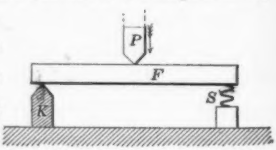

Fig. 2.

Fig. 3 shows the same arrangement, except that the spring *S* acts in tension and is supported by a bracket *B*, and, if the bar *F*, the knife-edge *K* and the bracket *B* are perfectly rigid, the entire energy of the blow from *P* will be absorbed in stretching the spring *S*.

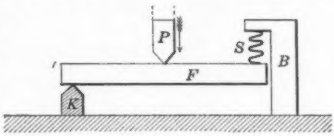

FIG. 3.

In order to lessen the strain on the bar *F* and on the knife-edge *K*, the point of application of the blow may be changed, as shown in Fig. 4.

Now, if we substitute in place of the spring *S* a test bar of metal we have an impact testing machine which will show the tensile resistance to impact of the material.

Let us now make another change in the arrangement. Place the knife-edge *K* vertical and substitute for the falling weight a pendulum swinging on a horizontal axis above and parallel to the fork-bar *F*, so that the pendulum *P* will strike a horizontal blow on the bar *F*, as shown in Fig. 5, which is a ground plan. Let the knife-edge *K* and the bracket *B* rest against independent piers, so that, when the specimen breaks, the fork-bar *F* will swing to one side and allow the pendulum to pass.

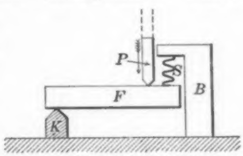

FIG. 4.

With this arrangement the pendulum may be raised to a given height and released. It will strike the bar *F*, tear the specimen in two and rise after the blow to a certain height. The difference between the height through which the pendulum fell and the height to which it rose after the blow shows the amount of energy absorbed in tearing the specimen. Fig. 5 may be said to show diagrammatically the form of machine used in the experiments herein described. From the foregoing it will be understood that by this method the specimens are broken by direct tension, and hence the tests may be called tensile impact tests.

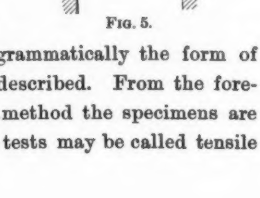

FIG. 5.

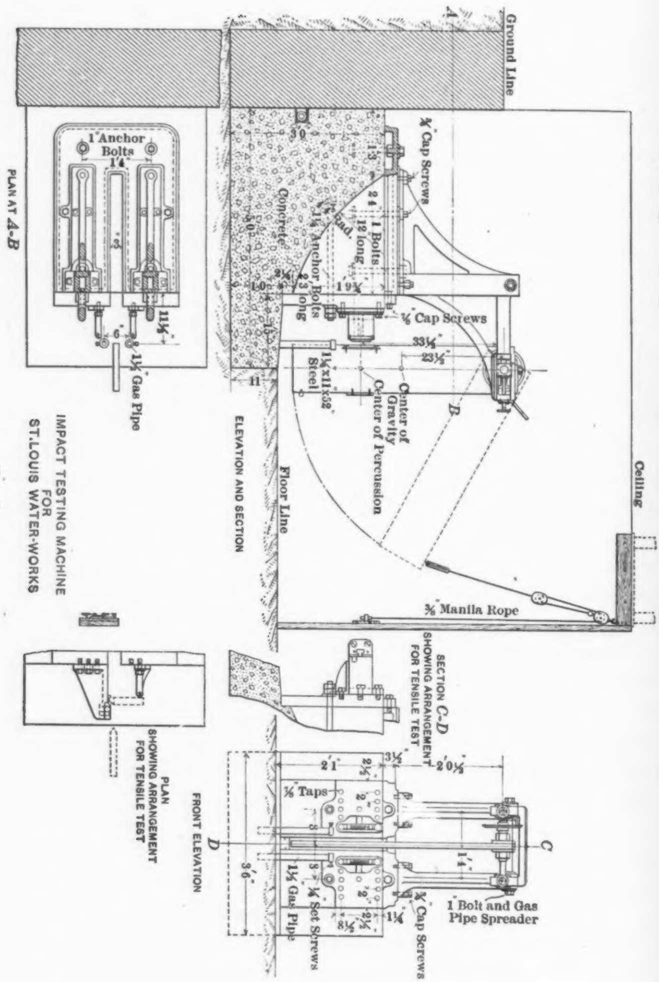
Ground Line
Ceiling
¾" Cap Screws
1" Bolts
12" long
Concrete
Anchor Bolts
⅞" Cap Screws
Center of Gravity
Center of Percussion
Floor Line
⅜" Manila Rope
ELEVATION AND SECTION
1" Anchor Bolts
PLAN AT A-B
1½" Gas Pipe
IMPACT TESTING MACHINE FOR ST. LOUIS WATER-WORKS
SECTION C-D SHOWING ARRANGEMENT FOR TENSILE TEST
PLAN SHOWING ARRANGEMENT FOR TENSILE TEST
FRONT ELEVATION
⅞" Taps
1½" Gas Pipe
¼" Set Screws
1" Bolt and Gas Pipe Spreader

Fig. 6.

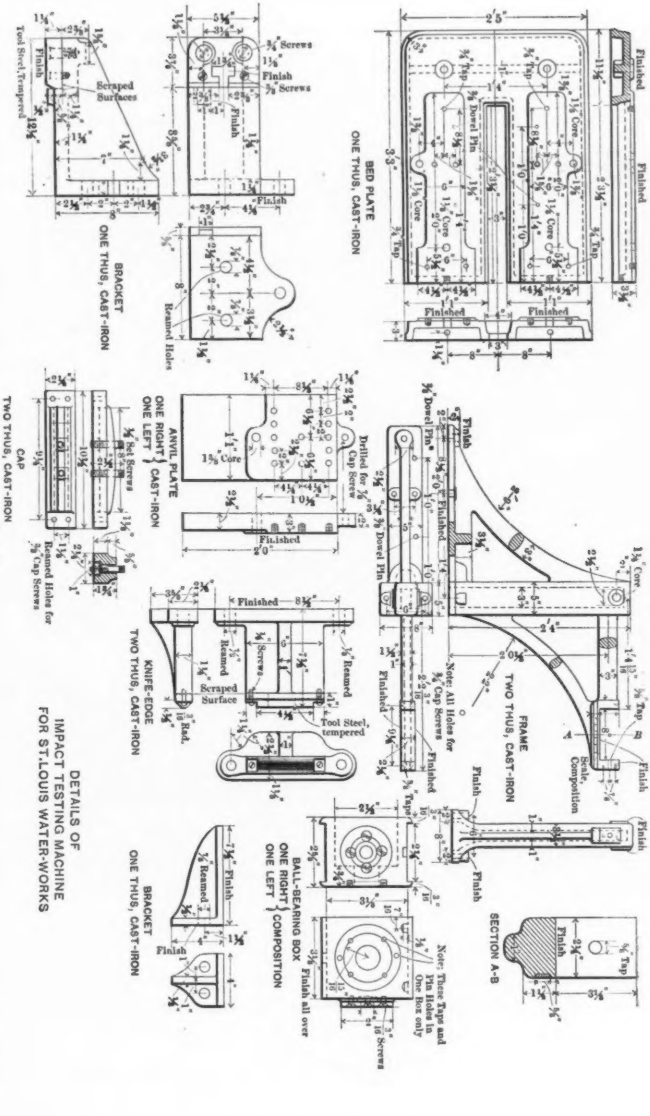

FIG. 7.

DETAILS OF
IMPACT TESTING MACHINE
FOR ST. LOUIS WATER-WORKS

The Testing Machine.

The testing machine used in the experiments has been partly described and illustrated in the *Transactions* of this Society.* The original machine was devised by the writer for making transverse tests by impact. The attachments by which tensile impact tests could be made were also devised by the writer. Mr. William F. Schaefer rendered valuable assistance in the execution of the scheme. The attachments for tensile tests were made in March, 1898. Figs. 6 and 7 show the form and some of the details of a new testing machine now being built for the St. Louis Water-Works Extension. In principle, the two machines are alike.

The new machine will have a pendulum or hammer of forged steel, rectangular in form and weighing about 200 lbs. It will hang on a

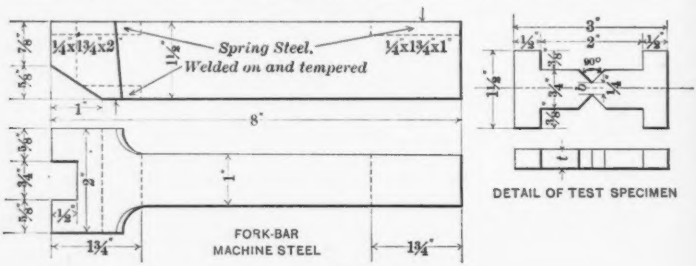

Fig. 8.

horizontal shaft resting in ball bearings. The striking edge of the pendulum and the fixed knife-edge will be of tempered tool steel.

The machine will be set up in a basement room, and the concrete anvil-block will abut against a stone cellar wall, below the level of the earth outside. By this arrangement the pendulum will swing clear of the floor of the room, and everything will be quite accessible and convenient. Plate I shows the frame and mechanism as assembled in the shop.

Fig. 8 gives the dimensions of the lighter fork-bar used. One of the fork-bars was made of machinery steel with faces of tool steel welded on at all bearings. These faces were tempered and then ground true. The other fork-bar was made of tool steel throughout, and tempered and ground at the bearings.

* "Experiments with a New Machine for Testing Materials by Impact." By S. Bent Russell, M. Am. Soc. C. E. *Transactions*, Am. Soc. C. E., Vol. xxxix, p. 237.

PLATE I.
TRANS. AM. SOC. CIV. ENGRS.
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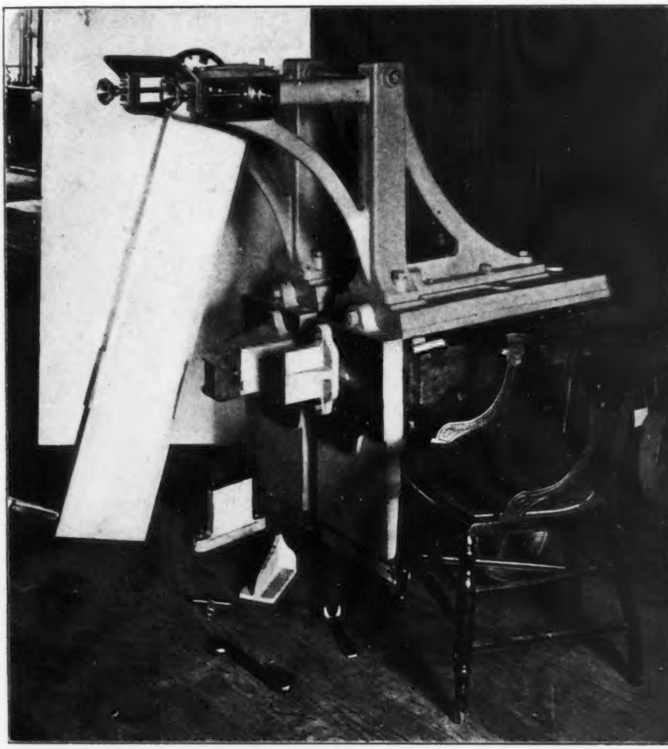

IMPACT TESTING MACHINE.

The bracket used is of cast iron. It is very heavy and rigid and is provided with a slotted plate of tempered steel. This plate receives the T-head of the specimen, and all bearing surfaces are ground true. There is a small shelf on the face side of the bracket which supports the fork end of the fork-bar when in position for a test. The other end of the fork-bar is held up by an adjustable support. When in position the axis of the fork-bar is on a level with the center of percussion of the pendulum.

The 7½ by 4-in. bracket, shown in Fig. 7, is used to support the heavy bracket while it is being bolted to the anvil plate.

In Fig. 6 two arrangements of the machine are shown. The first is for transverse impact tests, where two knife-edges are used.* The second is for tensile impact tests, where the bracket and fork-bar are used with one knife-edge only. In Plate I the parts are shown as set up for tensile tests.

In building these machines great care is taken to insure rigid supports. A solid concrete foundation is used, a heavy anvil plate is carefully bedded against the concrete, the seats of the bracket and knife-edge are planed off true, and the tempered steel striking plates are ground true on the seat and rest against scraped surfaces.

This care is necessary in order that there may be no springing in the joints when the blow is struck. The rule is that all fixed parts must be heavy and rigid, and all joints perfectly fitted and firmly bolted.

The hammer used in the experiments weighs 103 lbs., or about half what the new hammer will weigh. The relative proportions of its dimensions are the same as in the new hammer.

It is important that the hammer should strike on its center of percussion, so that there may be no blow on the trunnions. Where the hammer is of simple form, the center of percussion is readily computed.† After the hammer is set up, the center of percussion may be verified by timing the oscillations, the period of which should be the same as that of a simple pendulum, whose length is equal to the distance from the axis to the center of percussion.‡

The center of gravity of the pendulum or hammer is found by trial before mounting, and, at the same time, the hammer should be

* *Transactions*, Am. Soc. C. E., Vol. xxxix, p. 237.
† Johnson's "Materials of Construction," Art. 293.
‡ Rankine's "Applied Mechanics," Articles 544 and 607.

weighed, as the force of the blow is to be measured by the fall of the center of gravity in inches and the weight of the hammer in pounds. The pendulum is, of course, provided with an attachment for reading the height through which the center of gravity falls. The height through which the center of gravity rises after passing its lowest point is also shown.

We are now provided with a machine for breaking specimens in tension with a single blow. Before making actual tests, however, it is in order to consider what results will be obtained. In this paper the resilience of a specimen will be understood to mean its shock resistance or stopping power; that is, the amount of energy or work that will be required to rupture it. This energy will be expressed in inch-pounds.

If we raise the hammer 2 ins. and let it fall so as to break a specimen, and the hammer rises to a height of 1 in. after breaking the specimen, we would say that, as the hammer weighs 103 lbs., 103 inch-pounds of energy have been absorbed, so that the apparent resilience of the specimen is 103 inch-pounds. The loss due to friction in swinging is easily allowed for, therefore it may be considered that there is no friction.

In addition to breaking the specimen, there has been energy absorbed in other ways. The most important of these are the inertia and the springing of the fork-bar.

The Determination of Errors.

Problem: To Find the Loss due to the Inertia of the Fork-Bar.—According to Hodgkinson, the observed resilience is to the true resilience as $\frac{I + W}{W}$, when W is the weight of the hammer and I is the inertia of the test bar.* The problem is, then, to find I.

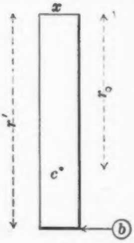

Fig. 9.

To simplify the problem we will assume that the fork-bar or the bar to be struck is a rectangular prism having its axis or fixed point at one end x, Fig. 9, and that it is struck at the other end. The length of the bar we will call r', and we will consider that the thickness and width of the bar are small enough to be neglected, or, in other words, that the bar is a straight line revolving about one end and having weight, but no width or thickness.

* *Transactions*, Am. Soc. C. E., Vol. xxxix, p. 239.

Let W_1 = the weight of the bar.

Let us now substitute, for our rectangular hammer striking on its center of percussion, an equivalent simple pendulum. Let b equal the weight of this simple pendulum.

We now have the case of the familiar ballistic pendulum ; treating the bar, whose length is r', as the ballistic pendulum, and the weight b as the projectile (see Fig. 9).

The formula for this case will be found in Rankine's "Applied Mechanics."* Taking the same notation as Rankine:

Let v = the velocity of the weight b before striking ;

r_o = the distance from the axis x to c, the center of gravity of the weight and bar together ;

W = the weight of the ball b and the bar together ;

l = the length of a simple pendulum equivalent to the combined mass revolving about the axis x ;

$B = \frac{W r_o}{l}$ = the portion of the joint weight to be treated as if concentrated at the center of oscillation, or a distance l from x ;

V = velocity of the center of oscillation of the joint mass at the instant of perfect contact, when both bodies are moving at the same velocity ;

g = the acceleration due to gravity.

Professor Rankine shows that $\frac{B\,V^2}{2\,g} = \frac{b\,v^2}{2\,g} \cdot \frac{b\,r'^2}{B l^2}$.

To find the value of $\frac{b\,r'^2}{B\,l^2}$:

Let W_1 = the weight of the bar alone;

Let I' = the moment of inertia of the joint mass $= (\frac{1}{3}\ W_1 + b)\ r'^2$;

Let $\rho^2 = \frac{I'}{W}$ = the square of the radius of gyration of the joint mass ; $l = \frac{\rho^2}{r_o}$.†

Substituting and cancelling out we find

$$\frac{b\,r'^2}{B l^2} = \frac{b}{\frac{1}{3}\ W_1 + b} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

which is the desired solution for the case of a hammer in the form of a simple pendulum.

*Article 607, p. 549. † Rankine, Art. 581.

To get this result in terms of known properties of the rectangular hammer: $b = \frac{W_2 R_2}{l_2}$.*

Where $W_2 =$ weight of hammer;

$R_2 =$ distance from axis of hammer to center of gravity of same; and

$l_2 =$ distance from axis of hammer to center of percussion of same.

Substituting in (1) we get:

$$\frac{b\, r'^2}{B\, l^2} = \frac{1}{1 + \frac{W_1\, l_2}{3\, W_2\, R_2}}; \text{ hence } \frac{B\, V^2}{2\, g} = W_2\, h \frac{1}{1 + \frac{W_1\, l_2}{3\, W_2\, R_2}} \quad \ldots\ldots (2)$$

$=$ effective energy,

where $h =$ the fall of the center of gravity of the hammer.

Let $W_2\, h = R'$, and $\frac{B\, V^2}{2\, g} = R$.

Then, from equation (2),

$$\frac{R'}{R} = \frac{1 + \frac{W_1\, l_2}{3\, W_2\, R_2}}{1} = \frac{\frac{W_1\, l_2}{3\, R_2} + W_2}{W_2} = \frac{I + W}{W},$$

where $I = \frac{W_1\, l_2}{3\, R_2}$ and W_2 is written as W, thus giving the value of I in Hodgkinson's rule.

Conclusion.—The inertia of the fork-bar may be taken as one-third of the weight of the bar by the ratio $\frac{l_2}{R_2}$, or the ratio of the radius of the center of percussion to the radius of the center of gravity of the hammer.†

This rule is, of course, only approximately true for a bar of the shape actually used. The true correction for the bar could be found by the same line of reasoning, taking all the dimensions into account.

In the method above given no account is taken of the deflection of the fork-bar, which is assumed to be inconsiderable.

The rule may be applied to one of the fork-bars used in the experiments as follows:

Weight of fork-bar No. 1 $= 6.39$ lbs.;

Weight of hammer $= 103$ lbs.;

$R_2 = 18$ ins.;

$l_2 = 25.75$ ins.

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* Rankine, Art. 607.

† Compare Merriman's "Mechanics of Materials," Articles 103 and 111.

As $W_1 = 6.39$, $\frac{W_1 l_2}{3 R_2} = \frac{6.39 \times 25.75}{3 \times 18} = 3.047 = I$, or the inertia of the bar in Hodgkinson's rule; and as $W = 103$,

$$\frac{I + W}{\mathrm{W}} = \frac{3.047 + 103}{103} = \frac{102.96}{100}\text{; hence } \frac{W_2 h}{R} = \frac{102.96}{100}\text{; or}$$

the total energy absorbed is nearly 3% greater than the resilience of the specimen, the difference being due to the inertia of the fork-bar.

As the error is directly proportional to the weight of the fork-bar, we would have with a fork-bar of half the weight an error of less than $1\frac{1}{2}$ per cent.

With any hammer of similar proportions, where the weight of the fork-bar is less that one-tenth of the weight of the hammer, the error due to the inertia of the fork-bar will be less than 5 per cent.

Problem: To Find the Error due to the Spring of the Fork-Bar.—We will consider the fork-bar as a beam supported at the ends and carrying a concentrated load. We first find the load P, which is determined by the maximum pull on the specimen at S_1 and the relative distances $S_2\,P$ and $P\,S_1$, Fig. 10. From the dimensions of the beam and the modulus of elasticity of the metal we may find the deflection y of the beam at the loaded point. With all dimensions given, we find that by the accepted formulas the load P is directly proportional to the reaction S_1 and the deflection y is directly proportional to P. Hence y is directly proportional to S_1, or $y = K' S_1$, where K' is constant.

FIG. 10.

The energy absorbed in producing this deflection is

$$R' = \frac{P\,y}{2} = \frac{K''\,S_1\,y}{2},$$

where K'' is constant. Substituting for y we get $R' = K\,S_1^2$, where K is constant, which means that the loss of energy in springing the fork-bar is proportional to the square of the maximum pull on the test specimen. K may be readily computed for given conditions by well-known formulas.

In this way the value of K for the light bar used in these experiments has been computed to be equal to 0.0000001106.

With this value, taking a specimen having an ultimate strength of 10 000 lbs. for example, we find that the springing of the bar will absorb the energy: $R' = KS_1^2 = 11.06$ inch-pounds, where $S_1 = 10\,000$

lbs. If the supposed specimen absorbed 400 inch-pounds in breaking, we would have an error of $\frac{11.06}{400} = 2.76$ per cent.

This may be considered an average case. If the specimen should have half the strength and half the resilience above given we would have half the percentage of error, or 1.38 per cent.

As a stiffer bar may be used with stronger specimens, it would seem that with metal of ordinary strength and ductility there should be no difficulty in keeping the proportionate error below 5%, and that without using so heavy a fork-bar as to involve a large error from inertia.

TABLE No. 1.—Resilience of Wrought Iron—Effect of Decreasing the Weight of the Fork-Bar.

Kind of wrought iron.	Resilience in Inch-Pounds per Square Inch of Section at Nick. R_2		Gain, per cent.
	With fork-bar weighing 6.39 lbs.	With fork-bar weighing 3.85 lbs.	
Tennessee common........	2 115	2 165	2.4
Tennessee charcoal........	2 885	3 046	5.5
Average gain.............	....	....	3.95

Note.—All the specimens of each metal were of the same form and dimensions, and were cut from the same bar. Each value of R_2 is the average of six tests.

Table No. 1 gives the results of experiments made to learn the effect of decreasing the weight of the fork-bar when other conditions are kept as nearly uniform as may be. The results show that the energy absorbed in breaking a specimen is greater with the light bar. This would seem to indicate that the error due to the springing of the fork-bar is greater than the error due to the inertia effect. The difference, however, may be due to variations in the metal.

Without further investigation, it seems fair to presume that the inherent errors of this method of testing need not exceed 10%, or, in other words, over 90% of the blow should be absorbed by the specimen itself.*

In making comparative tests with the same fork-bar, the error due to inertia is of no effect. In the results of the experiments no correction has been made for either the inertia or spring of the fork-bar. It is thought that, were all the corrections made, the comparative values would not be changed materially.

* See *Transactions*, Am. Soc. C. E., Vol. xxxix, p. 244.

Preparing Specimens.

Taking up first the design of the specimen bars, we find that on account of the great toughness or resilience of steel, it is necessary to test but a small volume of the metal. As it is difficult to confine the effect of a blow to a definite volume of metal, a nicked section was adopted, a standard nick of simple form being used.

In Fig. 8 is shown the dimensions of the specimen bars used. As they are all cut from flat sections, all the dimensions are constant, except the thickness t.

To allow for the varying thickness, the resilience of a specimen is divided by the area of the cross-section at the nick, and the result is called the resilience per square inch. The results are believed to be comparable.

It should be remembered, of course, that a test specimen of different form would not give the same resilience per square inch. Objection may be made to the use of any particular form of nick, but it is believed that tests made with the form adopted give a good idea of the quality of the metal. The blacksmith judges a bar of steel by nicking it and breaking it with his hammer and anvil. We are simply improving on his method by using a nick made to gauge, and measuring the energy of the blow. It may be added that it is not unlikely that the sharpness of the nick may result in a greater range of resilience values than would be obtained could the impact tests be made on a prism 6 or 8 ins. long, such as is tested in ordinary determinations of tensile strength and ductility. If this is true, then the form of nick should be made to suit the conditions which the metal tested will meet in service.

It is in order, perhaps, to note here that in the *Transactions** of the Society will be found the results of previous experiments made by the writer, in which nicked specimen bars of steel were broken by a single blow. In these previous experiments the bars were broken transversely. The great range in the values of resilience of steels tested in this manner led the writer to think that transverse breaking gave an unfair advantage to the softer steels. Hence, this study of impact tensile tests with nicked specimens of steel.

The specimen bars used in the experiments were cut to shape in a milling machine, as experience showed this to be the best way to secure sharp and uniform nicks. The milling cutters were ground in a

* *Transactions*, Am. Soc. C. E., Vol. xxxix, p. 237.

universal cutter and tool grinder, so as to secure a perfect cutting tool. A number of specimens are usually cut together on the milling machine.

Breaking Specimens.

The specimens are numbered and then calipered with a micrometer. A specimen bar is then placed in the bracket slot, and the fork-bar adjusted. The hammer is raised to a given height and released. It falls, strikes the fork-bar and breaks the specimen. The height to which the hammer swings is recorded. The proper correction for friction of the hammer is noted, and the observer is ready for another specimen. Table No. 2 shows the form of record kept.

TABLE No. 2.—Impact Test.—Office of Water-Works Extension. —St. Louis, October 27th, 1898.—Specimen of Wrought Iron (Tenn. Char.) Taken from Iron Company.—Tested for Tensile Resilience, with Results herewith Appended.

Lot No. 4. Weight of fork-bar, 3.85 lbs.

Experiment No.	Melt No.	Bar No.	Initial fall of hammer, in inches. F.	Rise after blow, in inches. S.	Correction for friction, in inches. C.	Thickness of plate, in inches. t.	Width at nick, in inches. b.	Area, in square inches at nick. $A = tb$.	Effective fall of hammer. $H = F - (S + C)$.	Total resilience, in inch-pounds. $R = 103\,H$.	Resilience per square inch, in inch-pounds. $R_2 = \frac{R}{A}$
1 112	*B*	1	1.80	0.13	0.03	0.231	0.230	0.05313	1.64	168.92	3 179
1 113	*B*	2	1.80	0.21	0.03	0.231	0.230	0.05313	1.56	160.68	3 005
1 114	*B*	3	1.80	0.18	0.03	0.233	0.230	0.05359	1.59	164.77	3 074
1 115	*B*	4	1.80	0.17	0.03	0.232	0.231	0.05359	1.60	164.80	3 075
1 116	*B*	5	1.80	0.29	0.03	0.232	0.230	0.05336	1.48	152.44	2 856
1 117	*B*	6	1.80	0.18	0.03	0.232	0.230	0.05336	1.59	164.77	3 087
										Average =	3 046

TABLE No. 3.—Resilience of Wrought Iron.—Effect of Increasing the Initial Fall of the Hammer.

Kind of wrought iron.	Initial fall of hammer, in inches. F	Number of tests made.	Resilience, in inch-pounds per square inch of section at nick. R_2
Tennessee common........	2	3	2 524
	4	3	2 488
Tennessee charcoal.......	2.5	3	3 549
	4.5	3	3 748

Note.—All the specimens of each metal were of the same form and dimensions, and were cut from the same bar.

TABLE No. 4.—NICKED IRON AND STEEL BARS.—RESILIENCE PER SQUARE INCH.

Bars nicked as shown in Fig. 8.

Metal.	Lot No.	Number of Melt.	Number of tests made.	Thickness of plate, in inches. t.	Resilience, in inch-pounds per square inch of section at nick. R_2.	Ultimate tensile strength, in pounds per square inch.*	Percentage of elongation in 8 ins.*
Iron, Norway.........	2	......	8	0.25	7 535	41 500	28.2
" Tenn. common.	3	A	6	0.25	2 506	55 000	21.2
" " charcoal.	4	A	6	0.25	3 648	52 500	27.5
" " " .	4	B	6	0.25	2 885	......	....
" " common.	3	B	6	0.25	2 115	......	....
" common........	5	A	6	0.25	2 176	50 700	14.2
" "	6	B	6	0.31	3 290	50 000	23.1
" "	6	C	6	0.37	2 140	52 500	18.1
" "	6	D	6	0.44	1 640	57 200	15.6
" "	6	E	6	0.50	3 500	54 800	19.6
" "	6	F	6	0.56	2 050	54 800	18.4
" "	6	G	6	0.62	2 030	52 800	19.0
Soft steel (plates)....	6	743	2	0.32	7 657	53 750	30.3
" " "	6	743	2	0.44	7 600	54 800	29.6
" " "	6	749	2	0.44	9 028	57 000	31.5
" " "	6	757	2	0.32	7 645	56 900	30.5
" " "	6	757	2	0.44	6 100	55 600	27.7
" " (angles)...	11	A	6	0.32	7 290	62 200	31.0
" " "	11	B	6	0.37	1 550	54 500	31.5
" " "	11	C	6	0.50	2 950	64 800	29.1

* The values in these columns are the result of one test only.

Table No. 3 contains the results of a few experiments made to show the effect of increasing the initial fall of the hammer. Apparently the effect is small compared with the variations in the metal.

Table No. 4 gives the values of resilience found with a number of samples of wrought iron and soft steel. In the last two columns are given for comparison the strength and ductility of each melt as shown by the ordinary tensile tests with the load applied gradually. The thickness t is in all cases the thickness of the plate or bar as rolled.

The steel of Lot No. 6 was basic open-hearth steel. The specimens were cut from large plates. The tests showed very uniform material. The steel of Lot No. 11 was said to be medium steel, but the tensile tests indicated that it should be graded as soft steel. These specimens were cut from angles about 3 by 3 ins. in size. These tests showed a lack of uniformity in the material. All the wrought-iron specimens were cut from bar iron.

On examining the values given in Table No. 4 we note that the highest value obtained with wrought iron is 7 535 inch-pounds per square inch, with ¼-in. Norway iron. The lowest value obtained with

wrought iron of the same thickness is 2 115 inch-pounds. Taking all thicknesses of wrought iron we get a range of from 1 640 to 7 535.

The highest test of steel is over 9 000 inch-pounds and the lowest is 1 550 inch-pounds.

In Melt No. 743 we get practically the same results with metal of different thicknesses, while in Melt No. 757 the thicker metal makes a poorer showing. This may be due to the thicker plate having been finished in the rolls at too great a heat.

A study of all the values given in Table No. 4 indicates that the resilience per square inch is not proportional to the ultimate strength, nor to the proportionate elongation, nor to the product of the two. We note, too, that the proportionate range in value is greater for the resilience than for either ultimate strength or elongation.

Conclusion.

In conclusion we may review the work briefly. The tests given were made by a new method of breaking small specimens in tension by impact. We find that there are two important errors which may be said to be peculiar to the method of testing. We find the first of these, or the error due to inertia, theoretically determinate. We find that the second of these errors, or that due to the spring of the fork-bar, is determinate to the degree that the tensile strength of the specimen is known. The other errors in the method are those common to all impact tests. We find that the results obtained are determined by the form of the specimen, and are hence only comparative.

We find that the tests that have been made by this method indicate that the resilience or shock resistance of rolled steel cannot be predicted from the tensile strength and elongation.

The values obtained will of course have but little other meaning until they have been interpreted by experience and by further experiment. It is suggested, however, that in time, tests of this sort may become a valuable aid in judging and recording the quality of structural steel.

DISCUSSION.

C. M. BROOMALL, Jun. Am. Soc. C. E. (by letter).—All impact testing machines necessarily give truly comparative results only under similar conditions of striking hammer, supports, foundations, etc. These conditions are not realized in practice, and the best that can be done is to so arrange matters that the greater portion of the energy of the blow will be absorbed by the specimen. If the proportion of energy absorbed by the specimen is very large, the error caused by the difference in the conditions of the apparatus will not affect materially the accuracy of the results. In the machine designed by the author it is believed that the energy absorbed by the specimen is more than 90% of the whole, so that the results given by it must be quite accurate. Mr. Broomall.

It seems to the writer, however, that a machine might be so designed that the specimen would absorb practically all the energy of the blow. Whether or not the mechanical details would be too complicated is another question. The suggestion is, to make use of a differential method of measurement, and, instead of mounting the specimen upon rigid supports, to mount it upon another pendulum initially at rest. If, then, after the impact, the rise of both pendulums be measured, the data are obtained from which to calculate the energy absorbed. This energy must have been entirely spent upon the specimen and its clamps. As these clamps are attached to the second pendulum, their weight must be added to it. The only energy not spent upon the specimen will be that absorbed in deflecting and producing angular motion of the clamps.

This differential method virtually amounts to suspending Mr. Russell's whole machine as a pendulum from the same axis as the striking pendulum, and so adjusting matters that the centers of percussion of the two pendulums are coincident with the point of impact.

S. BENT RUSSELL, M. Am. Soc. C. E. (by letter).—Since the paper was presented to the Society some further experiments have been made by the writer, and it is thought to be in order to present them briefly in closing this discussion. The experiments given in the paper were all made on the first impact machine, which has a hammer or pendulum weighing 103 lbs. The second machine, lately completed, has a hammer weighing 203 lbs. Mr. Russell.

In order to throw more light on the errors of this method of testing, a series of experiments was made, testing the same metal with the two machines.

Table No. 5 gives the results of these comparative tests. All the specimens of each lot were cut from the same bar. The fork-bar used weighed 3.86 lbs. The heavier hammer gives a higher result in one

Mr. Russell. case and a lower result in the other. This would indicate that increasing the weight of the hammer has no material effect on the result.

TABLE No. 5.—Effect of Increasing Weight of Hammer.

Metal, Wrought iron.	Lot No.	Resilience by 103-lb. hammer.	Resilience by 203-lb. hammer.
Tennessee charcoal.........	4	3 170	2 921
" common.........	3	2 169	2 325

Note.—Resilience is given in inch-pounds per square inch by tensile test. Test bar as shown in Fig. 8. Each value is the mean of six tests.

Similar comparative tests were made with cast-iron bars, broken transversely. All these tests showed a higher value of resilience for the 103-lb. hammer. The difference ran about 10%, indicating that the error of the machine is less with the heavier hammer.

Table No. 6 gives the results of tests made with the new machine since the paper was presented. The values may be compared with those of Table No. 4.

TABLE No. 6.—Nicked Steel Bars. Resilience Per Square Inch.

Bars nicked as shown in Fig. 8. Tested with 200-lb. hammer.

Metal.	Lot number.	Number of tests made.	Thickness of plate in inches. t.	Resilience in inch-pounds per square inch of section at nick. R_2.	Ultimate tensile strength in pounds per square inch.	Percentage of elongation in 8 ins.	Remarks.
Medium steel......	14	6	0.25	7 100	*61 240	24.0	6-in. channel, flange.
					§60 240	30.7	
Soft "	16	6	0.44	1 660	60 320	27.5	Angle bar of 60-lb. rail.
" "	18	6	0.50	2 800	53 980	31.1	Planed from 6 x ¾-in. bars.
" "	17	6	0.38	6 270	56 830	28.4	
High "	15	5	0.44	2 140	110 530	11.6	60-lb. steel rail.
Cast "	8	5	0.38	1 808	73 380	7.0	•
" "	9	6	0.36	4 120	......	....	

* Mill test, web.
§ Washington University test, flange.

The test of Lot No. 15 is of especial interest, showing that a high-grade steel may show an ultimate resilience, or resistance to shock, equal to that of a good grade of wrought iron. All these tests were made with a fork-bar weighing 3.86 lbs.

Now, in regard to the point raised by Mr. Broomall, it would seem to the writer that if such a machine as he describes were built, we would still fail in having all the energy of the blow absorbed by the specimen. In the case of tensile tests we would still have energy ab-

sorbed by the spring of the fork-bar, and on account of the inertia of the fork-bar. In transverse tests we would have energy disappear on account of the inertia of the specimen bar. The only losses which might be avoided by this device would be those due to the yielding of the fixed points of support. Now, from observations made upon the rigidity of these supports, it is believed that such errors may be made inconsiderable, in a properly designed machine, for all ordinary tests. Mr. Russell.

It might be profitable, however, to build such a machine as Mr. Broomall suggests, in order to determine more definitely and positively what energy is lost by yielding supports.